Wearable Oximetry for Harsh Environments

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***Abstract*— A wearable oximeter is needed to help people safely perform missions in environmental extremes. Key initial needs are to monitor for hypoxia at high altitudes, and to monitor for shock and hemorrhage during trauma. An initial investigation has been performed to assess design parameters for a wearable oximeter. Initial data was collected to assess the forehead, manubrium, and xiphoid process as wear locations; to assess required power; and to characterize the types and significance of motion artifacts that will need to be mitigated. The forehead was confirmed to be an excellent site with respect to signal quality, but signal corruption from changes in contact pressure will need to be mitigated. The sternal locations are initially assessed to be be more challenging, likely requiring more power and site-specific motion artifact mitigation.**

I. Introduction

Firefighters, first responders, warfighters, and explorers must often operate in environmental extremes of temperature (hot or cold), humidity, and high altitude. Heavy workloads and protective clothing add to the challenges of these environmental exposures. Wearable sensing is needed to maintain safety and maximize performance in these conditions by measuring physiological and cognitive status. Real-time physiological status monitors (PSMs) for thermal-work strain are maturing. These monitors typically measure heart rate (HR) from an electrocardiogram (ECG), skin temperature, and accelerometry.

Pulse oximetry [1] and photoplethysmography (PPG) are additional closely related sensing modes that are used ubiquitously in clinical settings, but especially in the case of oximetry, have not yet been addressed in a wearable form for harsh environments. These sensors would add three primary benefits to PSMs: 1) monitoring altitude sickness and acclimatization via SpO2 (peripheral oxygen saturation) [2], 2) detecting internal hemorrhage via a compensatory reserve index that operates on the raw PPG waveform [3], and 3) measuring HR and breathing rate from wear positions where the ECG is not measurable.

Considering these needs in slightly more detail, acute mountain sickness (AMS) becomes a significant health threat after a rapid ascent to high altitudes (> 2500m) [2]. Following decades of research, a model to predict AMS severity and prevalence over a broad range of conditions has been developed [2]. It is expected that AMS predictions will be further enhanced by individualized, real-time oximetry. As a related issue, hypoxia can occur among rotary-wing aircrews at these altitudes, and a rapid detection and response is needed to avoid accidents [4].

In the case of trauma, hemorrhagic shock is the leading cause of death, but is difficult to detect from standard vital signs because of the body's compensatory mechanisms [5]. Thus, promising results from the compensatory reserve index (CRI), computed from the raw PPG waveform, are quite significant [3,5]. Muscle oxygen saturation (SmO2) has also shown promise to quickly identify patients who need blood products for hemorrhage [6]. Although these trauma applications do not strictly require a wearable sensor, since the sensor can be applied while receiving care, it is advantageous to be able to quickly switch modes on a wearable sensor into a trauma-monitoring mode. In addition, the CRI and other oximetry-based measurements show promise for operational medicine where a wearable monitor is required. Related to this, commercial oximetry sensors (e.g., from Masimo, BSX Insight, Cercacor) are now being marketed for enhancing performance of elite athletes.

To address these applications, a monitor must:

- Measure oximetry, requiring at least two LEDs (typically red and infrared [IR]), as opposed to the typical consumer single-wavelength PPG HR sensors,
- Measure HR with 95% Limits of Agreement of better than ± 10 bpm,
- Be wearable, and compatible with equipment,
- Have a battery life of at least three days,
- Include signal processing that mitigates motion artifacts that result from field conditions.

Because we have not identified any commercial sensors that meet these needs [7], we have started to develop a prototype as a reference device. This paper describes initial progress relating to evaluating signal quality from candidate wear positions, power, and signal processing considerations. Candidate wear positions are the sternum, to allow

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integration with an ECG-based physiological status monitor that is under development, and the forehead. Key contributions of this paper are to: motivate the need for wearable oximetry, report initial data to assess two sternal wear positions that have received little or no prior investigation, and show that off-the-shelf electronics can now measure usable signals at low power levels that previously required complex, custom designs.

II. PRIOR WORK

A recent PPG review [8] summarizes the understanding of various wear sites, wavelengths, the effects of motion artifacts and contact pressure, and signal processing techniques to mitigate motion artifacts. This section provides additional details that are most relevant to our work.

A. Wear Locations

The wrist is the most popular wear site for consumer PPG-based HR monitors, but the accuracy of these wristworn devices is not sufficient for our needs [7,9]. Moreover, oximetry has not been measured reliably at the wrist in the presence of motion artifacts. Medical oximeters are worn most commonly on the finger, which is not a suitable location for wearing operationally, but forehead probes are also available. The finger-worn oximeters operate in transmissive mode, meaning that the LED and detector are positioned at opposite sides of the finger, whereas our work only considers reflective-mode oximetry, which is required for the sternum or forehead. A miniature battery-free oximeter has recently been reported that can be attached to a fingernail [10]. However, it is not clear that this would be suitable for multi-day wear in harsh environments, and the requirement for an external wireless power source may not be practical for these applications.

The sternum, in particular, the manubrium (upper sternum bone), has been considered by three groups, with mixed success. One group found difficulty in measuring SpO2, which led to a multiyear development of a complex sensor with 16 LED-detector pairs and sophisticated signal processing [11,12]. The measurement challenges were attributed to low perfusion. Another group was able to generate SpO2 comparable to a finger measurement, more simply through maximizing the LED drive current and optimizing a few other sensor parameters [13]. Moreover, they found that SpO2 reaction time was faster at the chest than at the finger. A third group prototyped an electronic patch that was designed to be worn on the sternum, but only verified the accuracy of the patch on the finger [14]. In our work, we consider the manubrium as a wear position, but also the xiphoid process (bottom of sternum), which is of special interest because that lies beneath a monitor worn on a chest strap. The xiphoid process wear position may differ significantly from the manubrium, because the latter provides a bone reflector, while the former is partially cartilaginous.

The forehead is known to be a well-perfused measurement site that benefits from a bone reflector. Moreover, when blood centralizes due to blood loss, shock or cold, a PPG signal is still measurable at the forehead after it is lost at the finger. Similarly, forehead measurements of SpO2 respond more quickly than at the finger, e.g. [4]. Medical forehead-mounted pulse oximetry probes are commercially available and research devices have also been prototyped [15,16]. In an evaluation of wearable PPG-based HR sensors, the only device that was as accurate as ECG-based devices was worn on the forehead [7]. This device's accuracy benefited from a lack of motion artifacts at the forehead, due to the particular data collection protocol, compared to numerous motion artifacts that degraded the accuracy of wrist-worn devices. However, significant motion and pressure artifacts were encountered in another evaluation of another device, which was worn together with a helmet [4].

The ear has also been investigated as an unobtrusive sensing location during sleep. An oximeter has been prototyped and tested for this purpose [17]. However, this device would not be expected to be wearable in the operational environments that we consider, at least not without considerable re-packaging and integration.

The green wavelength is well known to provide a strong modulation for measuring HR [8], as evidenced by nearly every consumer PPG-based HR monitor using green LEDs. However, for oximetry, red and IR wavelengths are the standard choices, in order to differentiate the spectra of oxygenated and deoxygenated hemoglobin. These various wavelengths have been assessed at different wear locations, although not at the sternum [18 - 21]. Green was assessed as the best wavelength at the wrist and finger, as expected, but IR was found to be as good or better at the forehead [21]. Our experience matches these assessments, in that we have found that red and IR show very little modulation from the heart rate, when measured at the wrist, but much better modulation when measured at the forehead.

B. Power

Power is not typically considered as a design parameter for medical oximeters, since they usually operate from wall power. Power consumption for the LED and processing of seven commercial transmissive-mode Nonin oximeters was found to exceed 50 mW [22]. With a focus on minimizing power, a single-chip oximeter (tranmissive mode on the finger) was designed with a total power of 4.8 mW for a 3% duty cycle, with the LEDs and control consuming 4.4 mW of the total. The LEDs' dominating of the total power is typical of oximeter power budgets [23]. Another prototype examined power reductions that could be obtained in a reflective-mode oximeter by adding two rings of detectors, surrounding the LEDs, in order to capture more of the light source [15]. When placed on the forehead, the peak LED current needed to maintain a target AC amplitude was 11.35 mA (8.5 for red and 2.85 for IR). This would appear to require considerably less power than the oximeter in [22]; for the same 3% duty cycle and operating at 3 V, the power would be about 1 mW. The tradeoff is that the rings of detectors result in a larger, more complex sensor. In [14], a wearable oximeter was built that incorporated custom annular photodiodes, inspired by the multi-detector approach [15]. In this device, LEDs were driven at 10 mA with a 14% duty cycle. Power reductions for these three oximeters were achieved through custom electronics. Our focus in this paper is to determine the possible power reduction with off-the-shelf, inexpensive components.

III. Data Collection Devices

To collect oximetry waveforms, we use the Maxim (San Jose, CA) 30102 reflective pulse oximetry module, which integrates red and IR LEDs, detector and supporting circuitry in a 5.6 x 3.3 x 1.6 mm package, mounted on a Maxim evaluation board that also includes a 3-axis accelerometer and microcontroller and PC software. Sample signals measured from the finger with the 30102 have been recently reported [24]. We have integrated the Maxim oximeter with a custom electronic data logger so that data can be collected without the oximeter being wired to a computer. All of the data included in this paper was measured with the Maxim oximeter. In ongoing work, we also use Masimo (Irvine, CA) multi-site and forehead oximeter probes, which we have modified so as to measure the analog waveforms using custom electronics. We use the BMEye (Amsterdam, NL) Nexfin with a Masimo finger probe as a gold standard, although these comparisons are not included in this paper.

Initial data has been collected from one subject at the forehead, manubrium, and xiphoid process. For forehead measurements, the Maxim evaluation board was integrated with an elastic headband repurposed from the Spree (Dallas, TX) HR monitor. For sternum measurements, the evaluation board was attached with Tegaderm (3M, Maplewood, MN). A total of 3.5 hours of raw waveform data has been collected while sitting, standing, and lying down.

The volunteer enrolled in the data collection after reading and signing an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects and the U.S. Army Medical Research and Materiel Command Human Research Protection Office.

IV. Results

Our initial investigation has focused on assessing the forehead, manubrium, and xiphoid process wear locations for signal quality, required power, and motion artifacts. Fig. 1 shows example signals, measured at 10 mA. The forehead signal is of high quality, as expected. The manubrium signal has a smaller, but measurable modulation. The xiphoid process signal also has measurable modulation, but with frequent significant motion artifacts; see left edge of the plot for an example. The effect on the modulation index (AC/DC) of varying LED current at the forehead is shown in Fig. 2. Higher modulation indices indicate better signal quality. (Since the SpO2 equation involves computing a ratio of the red and IR modulation indices, the modulation index is a natural figure of merit.) The modulation indices for red and IR at lower currents are comparable to those from 10 mA, suggesting that HR and SpO2 might be measured from as little as 2 mA LED current. This is significant, since previous work [15] required a much more complex, custom design to operate with similar currents.

An initial investigation of motion artifacts confirms that changes in contact pressure can significantly degrade the signal. Fig. 3 shows the results from applying pressure to the headband, resulting in barely detectable modulation.

Several signal processing algorithms will likely be needed to mitigate motion artifacts. One approach, illustrated in Fig. 4, was used to iteratively remove outliers from pulse interval (PI) sequences and SpO2 time series. A similar approach has been used for removing outlier heartbeat intervals from ECG data [25]. The local averages were computed using a 2nd-order Kalman filter [26]. The Kalman filter was applied within local 5-minute data windows in both the forward and backward time directions, and the average estimate at each time point from the two filtering passes was used. The PIs were first log transformed to produce distributions that are approximately normally distributed [25]. In each iteration, values with absolute deviations from the Kalman filter estimate greater than a threshold were removed, and Kalman estimates in subsequent iterations were made without these removed values. For both PI and SpO2, three iterations of outlier removal were applied. The thresholds for defining outliers in the three iterations were (0.5, 0.4, 0.3) for pulse intervals and (6, 4, 2) for SpO2 values.

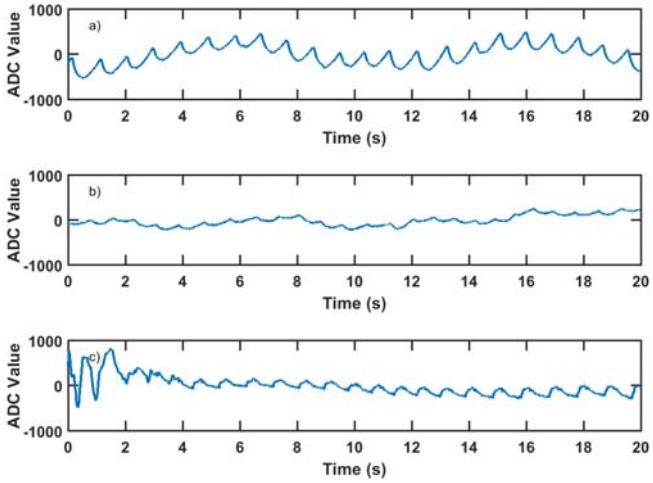

Figure 1. Example IR signals from a) forehead, b) manubrium, c) xiphoid process, 10 mA LED current, 4% duty cycle, sitting.

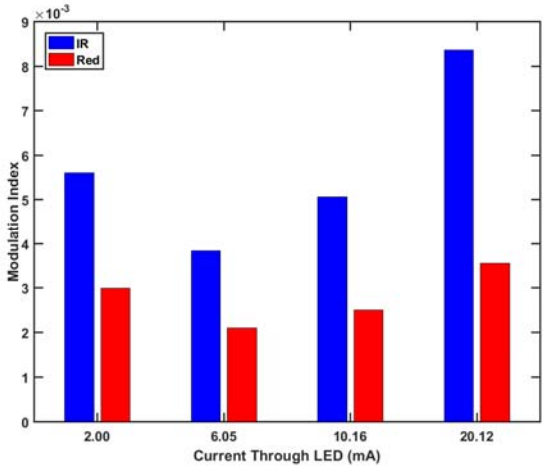

Figure 2. Red and IR modulation indices for varying LED current with 4% duty cycle, sitting.

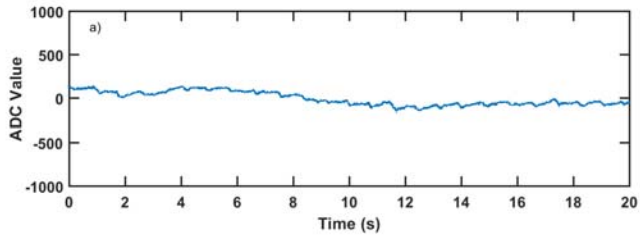

Figure 3. Example IR red signals from forehead while applying additional pressure to headband, 10 mA LED current, sitting.

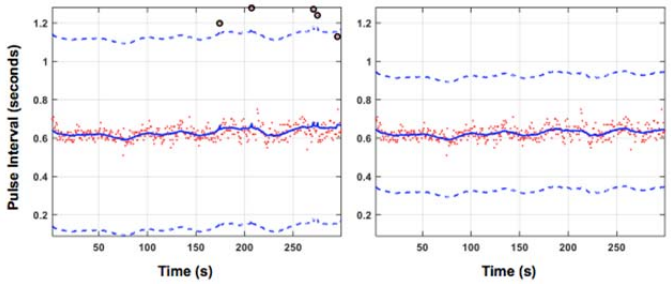

Figure 4. Example of multi-stage outlier rejection for pulse intervals; forehead, 10 mA, sitting. Red points are pulse-to-pulse measurements; blue line is smoothed result. First and final stage are shown, 2nd stage is omitted. Note outliers detected at first stage.

V. Discussion

An initial investigation has assessed design parameters for a wearable oximeter for operating in harsh environments. Initial data was collected from the forehead, manubrium, and xiphoid process as wear locations in order to assess required power, and to characterize the types and significance of motion artifacts that will need to be mitigated. The forehead was confirmed to provide excellent signal quality. However, artifacts due to changes in contact pressure would need to be addressed, probably through a combination of packaging design and signal processing. The acceptable LED current levels (≤10 mA for red and IR) should allow the oximeter to operate well over three days with a 100 mAh battery. Battery life may be further extended, after testing with users determines how often SpO2 measurements are needed for the key applications. The sternal locations will be more challenging, likely requiring more power and site-specific motion artifact mitigation. Next steps are to refine these initial results, to further test motion artifact mitigation techniques, and to build a wearable prototype.

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